Title:	Optimum tunes for the DARHT and Scorpius linear induction accelerators
Author(s):	Ekdahl, Carl August Jr.
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Optimum Tunes for the DARHT and Scorpius Linear Induction Accelerators

Carl Ekdahl

***Abstract*—A systematic approach to design of optimum magnetic focusing tunes for linear induction accelerators (LIA) is described. The magnetic fields used for focusing and beam transport must be strong enough to suppress beam breakup, yet not so strong that they induce envelope instability. Balancing these objectives, while also minimizing magnet power requirements, results in the optimum tune.**

I. Introduction

FLASH radiography of large explosively driven hydrodynamic experiments at Los Alamos is performed at the Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility using two linear induction accelerators (LIAs) to create the radiographic source spots [1]. These two LIAs use solenoidal magnetic fields to focus and transport the electron beams through the accelerators. A new LIA under development for flash radiography (Scorpius) will also use solenoidal magnetic fields for transport [2]. The strength of the solenoidal fields as a function of axial location is colloquially known as the magnetic focusing "tune." This article describes a systematic approach to the design of optimum tunes.

Practically, the tune of an LIA is an exercise in engineering trade-offs. In addition to transporting the beam with minimal envelope oscillations and emittance growth, the magnetic field must be strong enough to suppress the image displacement (IDI) and beam breakup (BBU) instabilities, but not so strong that it induces lattice or envelope instabilities due to periodic magnetic fields. Moreover, the tune should minimize the power required to suppress the instabilities. DARHT-II tunes have evolved to achieve these goals [3]. Figure 1shows the tune presently used on DARHT-II.

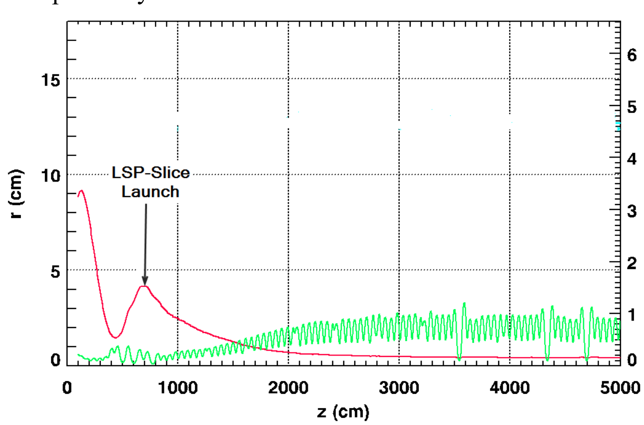

Figure 1: Magnetic tune presently in use on DARHT-II shown in green, along with simulated beam envelope radius shown in red (adapted from ref [3])

Tunes designed for Scorpius have also evolved as informed by simulation results. A tune designed for a distributed pumping evolution of the early version of Scorpius described in the Conceptual Design Report (CDR) [4] is shown in Figure 2. One of the tunes used for end-to-end simulations of Scorpius followed similar design considerations [5].

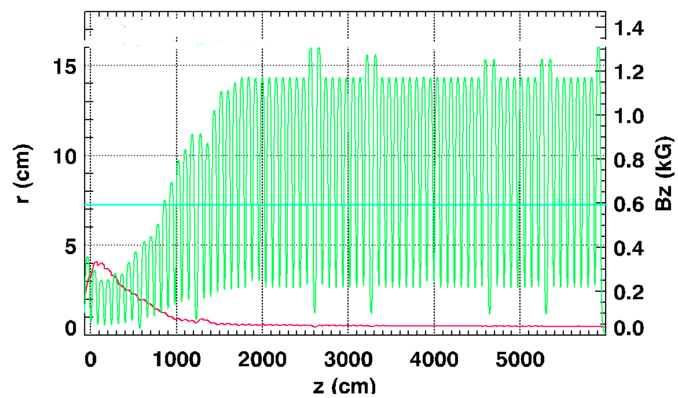

Figure 2: Magnetic tune designed for a recent distributed pumping version of Scorpius, along with simulated beam envelope radius shown in red.

The class of tunes in use on DARHT-II and intended for Scorpius (Figure 1 and Figure 2) characteristically have long regions of periodic magnetic field at high energy preceded by a region of increasing field to match the low energy beam to the periodic lattice. This optimizes the aforementioned constraints (See Appendix and ref. [4]).

A. BBU and IDI Stability

The tune design goal is a tune that adequately suppresses BBU [5]. The exponential growth factor for BBU is proportional to $\langle 1/B \rangle$, where B is the magnetic field on axis provided by the focusing solenoids. Therefore, a magnetic tune designed to reduce BBU should minimize $\langle 1/B \rangle$, subject to any other constraints.

For example, it has been shown that a tune with magnetic field increasing as $\gamma^{1/2}$ would minimize the phase advance for any given BBU amplification [6]. Initial tunes proposed for DARHT-II followed that principle, under the supposition that the linear dependence of corkscrew on phase advance derived for small amplitudes would extrapolate. Since then we have

- learned how to use steering dipoles to effectively combat corkscrew [7, 8, 9], and

- performed detailed simulations showing that corkscrew amplitudes saturate at modest amplitudes [4].

Relaxing the phase advance constraint opens up design space for other tunes, such as those shown in Fig. 1 and Fig. 2 (see Appendix).

Simulated growth of resonantly excited BBU in the Scorpius tune is plotted in Figure 3. This simulates experimental excitation with a tickler tuned to the resonant peak frequency. The amplification is about twice that observed in simulations of the nominal DARHT-1 tune [4]. To reduce the amplification to DARHT-I levels, one must either increase RF damping in the cell, or increase the magnetic field. BBU simulations with LAMDA show that a ~25% increase in the magnetic field would be sufficient, but one should approach any increase in magnetic fields with caution, because of the danger of envelope instability. Obviously, stronger focusing at the low-energy end would also help, but that depends on initial conditions of the injected beam, details of which may be unavailable.

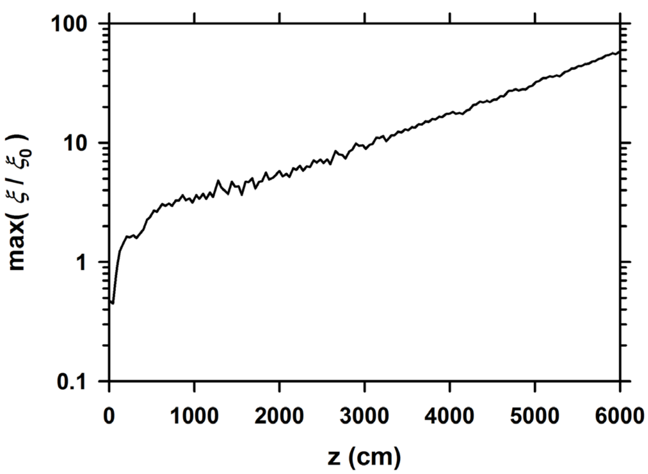

Figure 3: LAMDA simulation of resonantly excited BBU growth for the Scorpius tune. Excitation at the peak frequency of the main resonance simulates experiments using a tickler to excite the instability.

B. Envelope Instability

Periodic magnetic focusing fields can cause beam instability. These have been called lattice or envelope instability, depending on the theoretical model used to derive stability conditions. Derivations usually assume a coasting, constant energy beam transported through a periodic array of magnetic focusing elements. The simplest approaches based on single-particle motion or matrix optics predict instability when the phase advance per cell becomes greater than π [10, 11]. These inherent lattice instabilities manifest as periodic oscillations of beam size, growing in amplitude until the beam scrapes the beam tube. Here, the phase advance per cell is given by

$$\phi_\ell = \int_z^{z+\ell} k_\beta \, dz \qquad (1)$$

where ℓ is the length of the cell, and the betatron wavenumber is

$$k_\beta = \frac{eB}{2m_e c\beta\gamma} = \frac{B_{kG}}{3.4\beta\gamma}\ \mathrm{cm}^{-1} \qquad (2)$$

and the relativistic factors are $\beta = v/c$ and $\gamma = 1/\sqrt{1-\beta^2}$.

Adding the complication of space-charge to the problem introduces an additional envelope instability near $\phi_\ell = \pi/2$ [12]. Therefore, one must ensure that the focusing fields are not so strong that the phase advance per cell approaches 90 degrees.

Since the theory of these instabilities was developed for coasting beams they are not strictly applicable to accelerated beams in a periodic magnetic field. However, if the magnetic tune increases in proportion to the beam energy, then k_β may be periodic, or nearly so. Therefore, tunes should be designed so that $\phi_\ell < \pi/2$ throughout the LIA. For example, adapting the Scorpius design for distributed pumping to reduce the base pressure lengthened the gap-to-gap pitch by ~15%, and there is concern that further increases would be inviting instability. Moreover, instability might also follow any increase in magnetic field to further suppress BBU.

The phase advance for the Scorpius tune is illustrated in Figure 4. Clearly, one should approach any increase in magnetic fields with caution, because of the peak in ϕ_ℓ near 10m. One solution would be to increase the length of the matching section, thereby shifting the peak of ϕ_ℓ to the right, while at the same time increasing the peak fields in the periodic section to further suppress BBU.

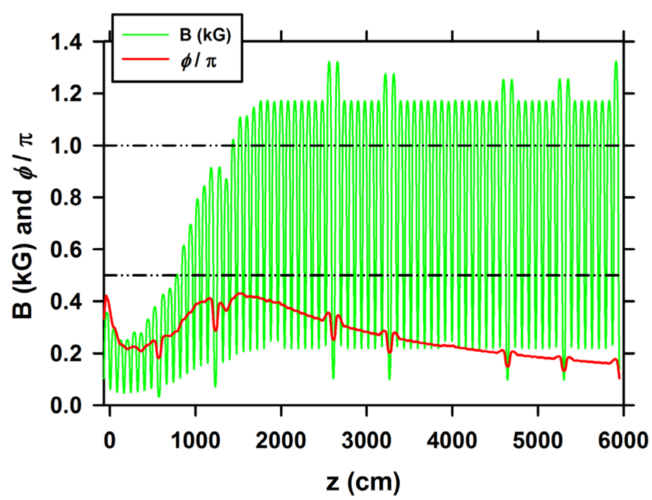

Figure 4: Phase advance per cell shown in red. Horizontal dot-dash lines show instability thresholds at $\pi/2$ and π .

A convenient way to test a tune for envelope instability is to launch a mildly mismatched beam, and observe whether the envelope oscillations grow. This can be readily simulated using the XTR envelope code. Results of such a test for the

Scorpius tune considered here shows no such growth, even for perturbations on the injected beam energy as great as 5% (the current was also perturbed to be consistent with diode perveance).

APPENDIX

The electron beam is transported through the Scorpius LIA using solenoidal magnetic focusing fields. This is an efficient and convenient means that has been used in all electron LIAs since the very first. Each accelerating cell has a solenoid incorporated into it, as well as dipole windings for steering. The magnetic field produced by these magnets is called the "tune" of the accelerator.

It has been shown that a tune with magnetic field increasing as would minimize the phase advance for any given BBU amplification [6]. However, other constraints have become more important. Among these are magnet power requirements and magnet heating. Therefore, we have considered a class of magnet-constrained tunes for Scorpius. These tunes are constrained by an initial field at the injector end that is high enough to suppress the image displacement instability, and a final field at the LIA exit that is limited by solenoid heating. Initial fields of 100G-200G are needed to suppress IDI, and a final field less than 2.0 kG will keep the temperature rise to less than 20C in present magnet designs.

For example, consider a continuous transport field increasing as

$$B(\gamma) = B_0 + (B_f - B_0)\left(\frac{\gamma - \gamma_0}{\gamma_f - \gamma_0}\right)^p \qquad (3)$$

With a constant accelerating gradient $\gamma = \gamma_0 + z d\gamma / dz$, and $\Delta B = B_f - B_0$ one has

$$B(z) = B_0 + \Delta B\left(z / L\right)^p \qquad (4)$$

Setting $p = 1/2$ is approximately the phase advance constraint of ref. [6] for this field constrained tune. The field profile for this family of tunes is shown in Figure 5 for $B_f = 1.5\ \text{kG}$ and $B_0 = 200\ \text{G}$.

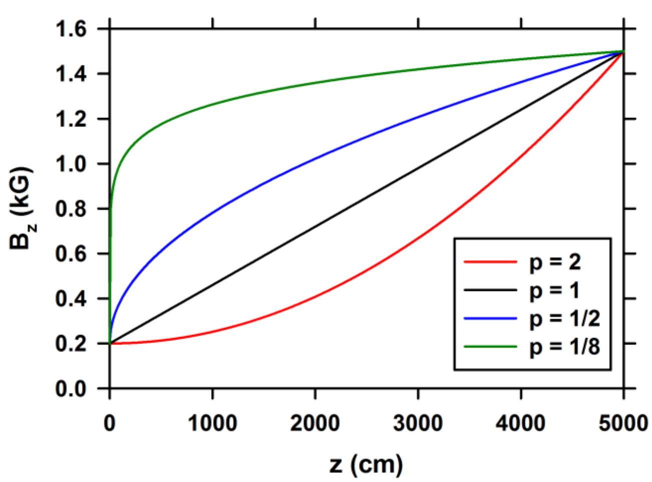

Figure 5: Continuous tune profiles according to Eq. (3).

Figure 6 shows how $\langle 1/B \rangle$ can be reduced to suppress BBU reducing the exponent p, thereby "flattening" the profile. With these magnet constraints it is clear that a significant suppression of BBU growth can be achieved through flattening of the tune profile

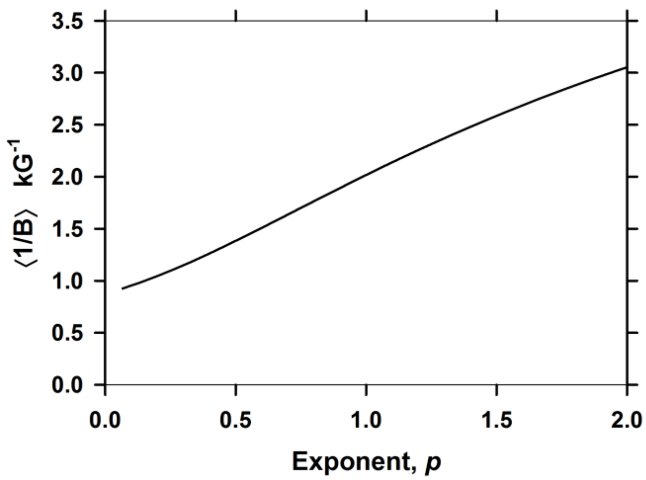

Figure 6: BBU damping factor as function of the exponent in the tune profile (smaller is better!).

Since the energy stored in this magnetic field is proportional to the integral of $B^2 / 2\mu_0$, the power required to maintain the field is clearly minimized by reducing p . Thus, reducing p to flatten the profile not only increases BBU suppression, it also is a more efficient use of the power supplies for energizing the field.

The tuning strategy that was used on DARHT-II was to begin with p=0.5 to minimize corkscrew, and then adjust downward as when corkscrew was found to be less of a problem. The flattened tune presently used on DARHT-II is shown in Fig. 1. Tune designs for Scorpius have followed the same path, and a flattened tune is shown in Fig. 2.

ACKNOWLEDGMENT

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